Revealing the role of land-use features on macrolitter distribution in Swiss freshwaters

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Abstract

Macrolitter and especially macroplastics (> 0.5 cm) negatively impact freshwater ecosystems, and can be retained along lake shores, riverbanks, bed sediments or floodplains. Long-term and large-scale assessments of macrolitter on riverbanks and lake shores provide an understanding of litter abundance, composition and origin in freshwater systems. Combining macrolitter quantification with hydrometeorological variables allow further study of leakage, transport, and accumulation characteristics. Several studies explored the role of hydrometeorological factors in influencing macrolitter distribution and found that river discharge, runoff, and wind only partially explains its distribution. Other factors, such as land-use features have not yet been thoroughly investigated. In this study, we provide a country-scale assessment of land-use influence on macrolitter abundance in freshwater systems. We analyzed the composition of the most commonly found macrolitter items (referred to as 'top items', n = 42,565) sampled across lake shores and riverbanks in Switzerland between April 2020 and May 2021. We explored the relationship between eleven land-use features and macrolitter abundance at survey locations (n = 143). The land-use features included buildings, city centers, public infrastructure, recreational areas, forests, marshlands, vine-

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yards, orchards, other land, and rivers and canals. The majority of top items are significantly and positively correlated with land-use features related to urban coverage, notably roads and buildings. Over 60% of top items were found to be correlated with either roads or buildings. Notably, tobacco, food and beverages related products, as well as packaging and sanitary products, showed strong associations with these urban land-use features. Other types of items however, did not exhibit a relationship with land-use features, such as industry and construction related items. Ultimately, this highlights the need to combine measures at the local and regional/national scales for effective litter reduction.

Keywords: Macroplastic, Microplastic, Water quality, Plastic pollution, Rivers, Lakes, Contaminants, Marine debris, Transport, Accumulation

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1. Introduction

Macrolitter is an ubiquitous environmental risk, affecting both aquatic and terrestrial ecosystems (van Emmerik and Schwarz, 2020). A growing amount of observational evidence shows high levels of exposure of freshwater ecosystems to macrolitter, with plastic found as the dominant material (van Emmerik et al., 2020). Macroplastics can threaten ecosystems, injure animals, cause economic damage by clogging hydraulic infrastructures, and lead to increased urban flood risks (van Emmerik and Schwarz, 2020; Azevedo-Santos et al., 2021). Despite these threats, the leakage processes and transport pathways of macrolitter in freshwater systems remain largely unknown. Large-scale quantification of macrolitter abundance in freshwater systems have only been undertaken recently (Barer and Kull, 2018; Hengstmann and Fischer, 2020; van Emmerik and Schwarz, 2020; González-Fernández et al., 2021). As a result, only a handful of studies have so far explored the drivers of macrolitter variability in freshwater systems (Roebroek et al., 2021b; Cowger et al., 2022; Schuyler et al., 2022; Tasseron et al., 2023). Additional research on this would be essential for guiding effective litter reduction and mitigation strategies.

The most commonly used methods to quantify macrolitter sample either the freshwater surface or lake shores and riverbanks (Castro-Jiménez et al., 2019; van Emmerik et al., 2019; Mason et al., 2020; van Emmerik and Schwarz, 2020; Tasseron et al., 2020). Floating macrolitter assessments typically use visual counting of macrolitter items from bridges or deploy nets to retrieve water samples from boats or bridges. These monitoring techniques require the presence of infrastructure or the availability of equipment. In addition, they only provide a 'snapshot' view of the quantity and composition of floating litter at a given time. By contrast, monitoring macrolitter abundance on river and lake banks allows to cover larger geographical areas and to conduct more frequent observations (Vriend et al., 2020). As a result, some countries have deployed large-scale monitoring programs of macrolitter abundance along riverbanks and lake shores, often relying on the participation of trained volunteers. This is the case in the Netherlands with the *Schone Rivieren* (Clean Rivers) initiative (van Emmerik and Schwarz, 2020), the Swiss Litter Report in Switzerland (Barer and Kull, 2018) and the Great Canadian Shoreline Cleanup (Hengstmann and Fischer, 2020). These large-scale and long-term monitoring programmes provide baseline estimates of macrolitter quantities and composition. They can also be used to explore fundamental transport and accumulation processes of macrolitter in freshwater systems.

Despite baseline assessments of macrolitter in freshwater ecosystems becoming more common, the factors determining its variability remain to date largely unresolved. Macrolitter found on riverbanks and lake shores comes either from terrestrial pathways (by direct littering or dumping) or from transport from the aquatic systems (by river flow and lake currents) (Mellink et al., 2022; Roebroek et al., 2021b). It is commonly assumed that hydrometeorological variables, such as precipitation, wind speed, water flow velocity and river discharge play an important role in the transport and deposition of macrolitter items along the banks of freshwater bodies (Liro et al., 2020; Bruge et al., 2018; Haberstroh et al., 2021; Roebroek et al., 2021b). Other factors affecting macrolitter transport and accumulation processes pertain to the items characteristics (e.g. buoyancy, level of biofouling) and the aquatic system characteristics (e.g. meanders and channel width in the case of rivers) (Lechthaler et al., 2020; Lobelle et al., 2021; Newbound, 2021). Macrolitter abundance on riverbanks and lake shores can also come from mobilisation through terrestrial pathways (Mellink et al., 2022). In this case, wind speed and surface runoff are also presumed to be major drivers of macrolitter transport (Lebreton et al., 2017; Meijer et al., 2021; Roebroek et al., 2021b). A study on macrolitter abundance on the Dutch riverbanks demonstrated the influence of hydrometeorological factors, but also highlighted that the studied variables (wind speed, flow velocity and precipitation) only accounted for 19% of macrolitter variability (Roebroek et al., 2021b). Similarly Tasseron et al. (2023) investigated the relationship between some environmental drivers such as rainfall, sunlight, wind speed, and tidal regimes and macrolitter transport, revealing minimal and statistically insignificant correlations. Other potential driving factors have not yet been studied in relation to macrolitter abundance and composition in freshwater systems but may play an important role. These include partially stochastic events such as direct littering and dumping of macrolitter close to freshwater systems (Cieplik, 2021). These actions are driven by individual human behavior, which can vary significantly due to factors such as personal habits, convenience, awareness of proper waste disposal, and even mood or emotions at the time of disposal. A crucial open question is the role of local leakage processes in macrolitter presence along lake shores and riverbanks. In this study, we investigate the impact of differing land-use features on macrolitter quantities, considering items origin and composition. This could ultimately improve our understanding of leakage and (terrestrial and aquatic) transport mechanisms of macrolitter into freshwater systems. Additionally, it could provide an initial step to differentiate between locally and non-locally leaked items, as well as items transported for short distances and items travelling long distances before beaching.

Land-use features are an explaining factor for variability in macrolitter accumulation in coastal, marine and land environments (Aydin et al., 2016; Grelaud and Ziveri, 2021; Harris et al., 2021; Pietz et al., 2021) but no such studies have been conducted for freshwater systems. The proximity of land-based litter sources, such as recreational and urban areas might be an indicator for high leakage rates (i.e. high littering rates and losses into the environment). Impervious surfaces also generate higher surface runoff volumes, which in turn can accelerate leakage and propagation of litter from land to the aquatic environment (Baldwin et al., 2016). Many regional and global scale studies model plastic waste inputs into lakes, rivers and oceans as a function of nearshore population densities, generally using global population datasets (Jambeck et al., 2015; Hoffman and Hittinger, 2017; Lebreton et al., 2017; Schmidt et al., 2017). However, higher human densities do not necessarily translate in higher rates of leakage into the environment at a local scale (Schuyler et al., 2021). This highlights that population density should not be used as the sole proxy for litter inputs for accurate modelling of its distribution in the environment. Land-use features may play an important role in macrolitter accumulation, as they can highlight specific point sources of macrolitter items, such as industries and commercial areas. Additionally, they provide insight into the level of visitation at places, such as recreational areas, which could lead to higher leakage rates into the environment. The role of several land-use features should be considered but has so far not been thoroughly quantified in relation to empirical data on macrolitter abundance. Such insights are relevant for several reasons. First, a better understanding the leakages and transport processes of litter pollution is crucial in designing targeted intervention strategies and formulating policies to prevent and reduce their leakage into the environment. Second, they can be used for improving large-scale models on debris distribution and propagation into the environment.

In this study, we elaborate on the hypothesis that land-use features (partially) explain the variability in macrolitter abundance and composition in freshwater systems. We used an extensive observational dataset on macrolitter abundance, collected across Switzerland in 11 lakes and 17 rivers (Figure A.1). 386 surveys were conducted over a 13-month period, during which 50,649 macrolitter items were sampled on Swiss riverbanks and lake shores. We analyzed the composition and likely origin of the most commonly found macrolitter items (n = 42,565) - hereby referred to as 'top macrolitter items'. We then assessed the role of eleven land-use variables (buildings, city centers, recreational areas, public infrastructure, roads, forests, marshlands, vineyards, orchards, other land and rivers and canals) on macrolitter abundance among top items. Based on this analysis, we provide insights on the role of land-use features in macrolitter abundance in freshwater systems.

2. Data and Methods

Macrolitter dataset

The macrolitter data used in this research was collected between 1 April 2020 and 31 May 2021 by the Non-Governmental Organization (NGO) Hammerdirt. Overall, 386 surveys were conducted at 143 locations, in 98 different municipalities in Switzerland (Figure A.1). A total of 50,649 macrolitter items were counted and categorized. Of the 386 surveys, 331 (85.8%) were undertaken along lake shores and the remaining 55 (14.2%) along riverbanks. The surveys were conducted by Hammerdirt staff and trained volunteers (two surveyors on average per survey). Several criteria determined the selection of the survey locations. Firstly, the survey area had to be a bank of a lake or river, with direct contact with the water. Small ponds and streams were excluded, and the survey locations typically comprised between 50 and 200 m^2. Secondly, survey locations were required to be accessible (both physically and legally) throughout the year. Also, the site had to be within 30 minutes of the nearest public transport station to ensure that surveyors could easily reach it. Finally, survey locations that had already been selected for the national Swiss Litter Report (Barer and Kull, 2018) in 2018 were preferred to facilitate future time-series analysis. In addition to the macrolitter sampling, the surveyors also measured the length and width of each survey location. The length of the sampling area was determined as the longest continuous stretch of lake shore or riverbank accessible. Despite international protocols such as OSPAR requiring to survey areas of 100 m of length (Ospar Commission, 2010), this was not possible in the Swiss context, given that the majority of beaches have smaller strips of land available (due to both legal and physical barriers), with a site median length for the surveys considered in this study of 45 m. The width of the survey area was defined as the distance from the waterline to the high-water line. The high-water line is intended as the mark left by the highest water level reached during a particular period, such as during a flood or a period of high water flow.

During each survey, participants collected all visible items > 5 mm in size (i.e. macrolitter). Items were subsequently categorized using the Marine Litter Beach item classification, which contains a total of 217 categories (Marine Strategy Framework Directive Technical Subgroup on Marine Litter, 2013). To minimize the propagation of uncertainty, we chose not to convert the item count to mass statistics or other metrics related to transport and accumulation on lake shores and riverbanks (de Lange et al., 2023). The measurement process itself introduces inherent uncertainty, which includes potential misclassification of items by observers and the possibility of missing some items. To minimize the uncertainty, we grouped the survey results by riverbank and lake shore locations, as the grouping helps to average out individual measurement errors. It is unclear how representative the survey locations are of the level of macrolitter pollution of all lake shores and riverbanks in Switzerland. To date, no comprehensive studies quantified the uncertainty associated with macrolitter surveys, making it challenging to provide a precise estimate of the uncertainty in our measurements. Further research is needed to address this knowledge gap and enhance our understanding of the uncertainties inherent to macrolitter surveys.

All items collected and analyzed during each survey were also categorized by material types (plastic, glass, metal, textile and paper). We indicated for each item category their likely type: plastic fragments and pieces, industry and construction, tobacco, food and beverages, sanitary, non-food packaging, and others. This classification by items type was done by using the description of each macrolitter category as an indicator for the type and origin of items. Items for which no clear type could be inferred from the category description were categorized as 'others'. We considered expanded polystyrene (EPS) under the industry and construction type. In Europe, this plastic item is mainly used as insulation material in the construction sector (Kawecki and Nowack, 2019; Lobelle et al., 2023). Macrolitter abundance was ultimately reported in both total items count and number of items/100 m of shoreline, in line with the EU Marine Litter Baselines, which express marine macrolitter abundance in items/100 m of shoreline (Marine Strategy Framework Directive Technical Subgroup on Marine Litter, 2013).

Land-use dataset

We used the Swiss Land Use statistics (Federal office of topography Swisstopo, 2023) to extract land-use features at each survey location. This dataset is freely available and is updated every year. The land-use dataset is available in vector format and covers the entire country. The precision ranges from 0.2 m to 3 m, depending on the features. Among the land-use features extracted in this dataset, the following are identified: 1) Buildings 2) City centers 3) Recreational areas 4) Public infrastructure 5) Vineyards 6) Orchards 7) Marshlands 8) Forests 9) Rivers and canals, and 10) Roads. While these are the most prominent land-use features, other land-use types were present in the dataset, such as barren rocks, cliffs and glaciers. However, their presence in the survey locations is marginal compared to the ten extracted features and we did not include them in our analysis. The land-use dataset does not cover all the terrestrial land, and we thus generated an eleventh feature, called 'Other land', for all the areas not covered by the features listed above. A visual inspection using Google aerial imagery showed that these areas are mainly covered by fallows, pastures and grasslands.

The feature 'Buildings' refers mainly to residential houses and buildings. Recreational areas include diverse public uses, from sport fields to camp sites and captures all land surfaces dedicated to social activities. City centers identify the central areas of urban agglomerations. Public infrastructure includes schools, hospitals, prisons, cemeteries, administrative buildings. The feature 'Roads' refers to all roads intersecting the buffer area, from small paths to highways. Rivers and canals include all rivers and canals within the buffer area and that intersect the lake shores or riverbanks of the survey location. All land-use features except roads and rivers were expressed in km^2 and in percentage (%) of the total terrestrial surface of the buffer area around the survey location. To determine the total terrestrial surface, lake and river surfaces were subtracted from the total surface. Roads and rivers features are expressed in km. Table A1 in Appendix A details the land-use characteristics for both lake and river survey locations. The dominant land-use class is buildings (49.1% and 41.5% for lake and river locations, respectively), followed by other land areas (21.1%-27.7%) and forested areas (17.6%-19.4%). The other land-use features represent much lower shares of the land-use ($< 10\%$). The average length of the road network across survey locations is comprised between 55.6 km and 10 km; and the average length of rivers and canals is between 1.0 km and 6.2 km (Table A1).

We extracted the above-mentioned eleven land-use features at each survey location. This involved defining a buffer area of 5.8 km^2 (1,500 m in radius) around each survey location and extracting land-use features of interest for each area (Figure 1). The buffer size was based on the average overland macrolitter transport distance (1500 m) found by Cowger et al. (2022). We chose a hexagonal shape for the buffer area as it offers several advantages for potential mapping of an entire territory (Birch et al., 2007). Firstly, the hexagonal shape provides a more uniform coverage of a territory compared to circles. This ensures that no gaps or overlaps occur between adjacent buffer areas, allowing for a comprehensive and accurate representation of the land-use features within the territory. Secondly, the hexagonal shape allows for efficient and systematic sampling or grid-based analysis. The regularity and symmetry of the hexagons facilitate consistent spatial arrangement and enable easier interpretation and comparison of the land-use data. Thirdly, the hexagonal shape minimizes edge effects and distortions, unlike squares or rectangles (Birch et al., 2007).

Correlations between land-use variables and macrolitter abundance

To determine the commonly found items, we considered those that were observed at least 20 times during the sampling period. For each of these commonly found items, we correlated their abundance (expressed as items per 100 meters) with various land-use features. The correlations between land-use features and the top macrolitter items were calculated using the Spearman correlation analysis, which tests for statistically significant monotonic relationships between variables (Glasser and Winter, 1961). The null hypothesis tested was that there is no correlation between the land-use features and the top items. The test results provide information about the direction (R) of the correlation and whether the association is likely due to

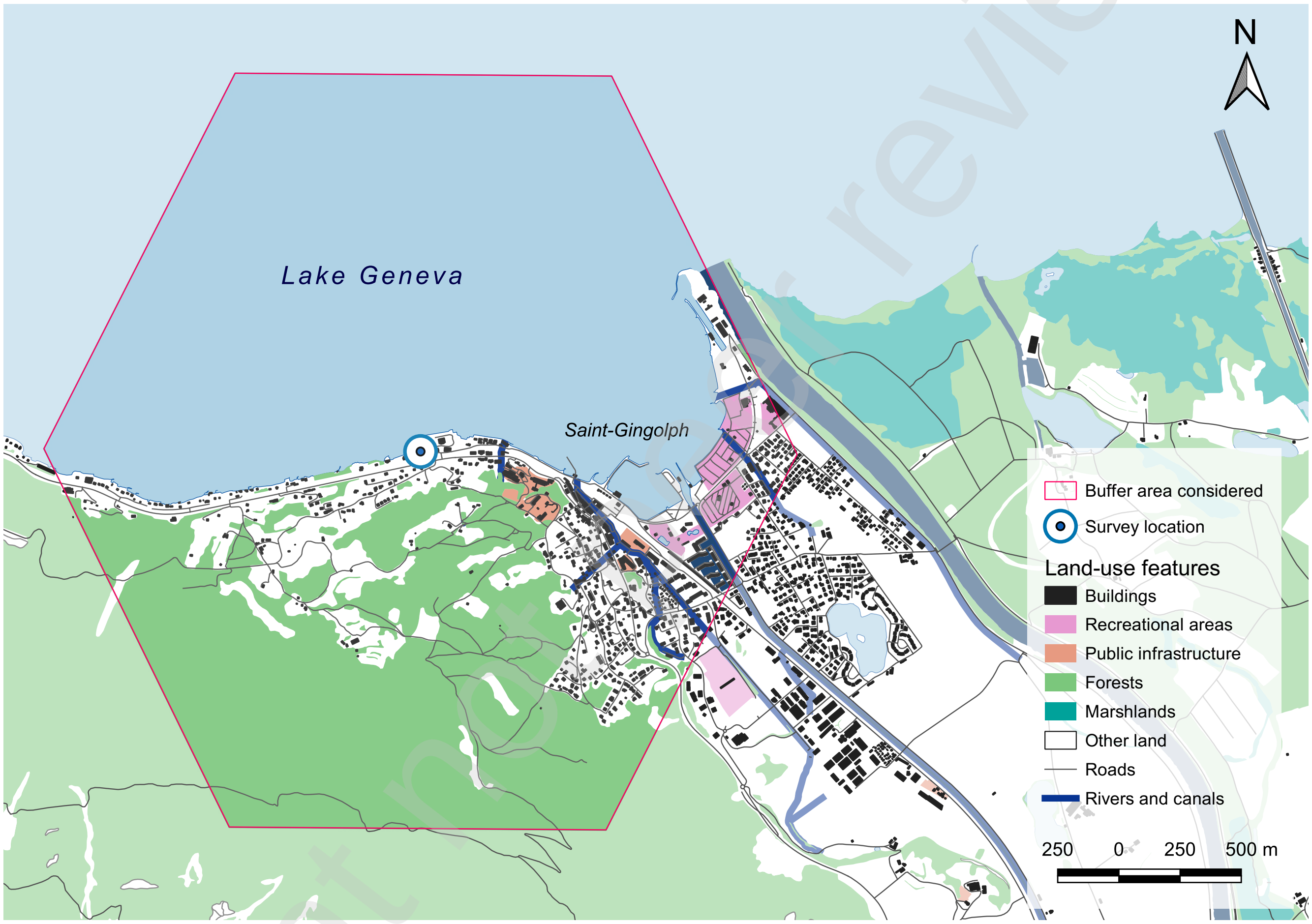

Figure 1: Example of land-use features present in one buffer area around a survey location. The example is from the Saint-Gingolph survey location (46.387746, 6.843686) at Lake Geneva, Switzerland. Note that not all land-use features are present at this location and thus not all are displayed on the map.

chance (p-value). We consider the correlation statistically significant if the p-value is less than 0.05. We only report correlations that are statistically significant, as correlations below this threshold are deemed too uncertain. It is important to note that the Spearman correlation analysis provides an indication of the relationship between land-use features and macrolitter abundance, but it does not establish causation, as other factors may also contribute to the observed association.

In Table 1, we formulate hypotheses for the possible correlation signs between the land-use features and macrolitter abundance. A positive (and significant) correlation would indicate that macrolitter abundance increases with an increase in the coverage of land-use feature considered. The substantiation of the hypotheses is mainly derived from existing observational studies. Given that understanding the relationships between land-use features and macrolitter abundance is mainly unresolved, for most variables two opposite correlations could be hypothesized. For instance, it is yet unknown whether rivers act more as plastic reservoirs or pathways of plastics (van Emmerik et al., 2022) and thus whether rivers mainly deposit items on theirs banks or re-mobilize previously accumulated items and carry them further downstream. Both roles can coexist, as well as vary depending on space and time, river characteristics, hydrological conditions and item characteristics.

Table 1: Hypotheses for correlations between macrolitter abundance and land-use features. '+/-' signs indicate that the correlation sign is expected to be either positive or negative. For some variables, two diverging hypotheses are formulated. The first one is considered the most likely one.

Variables	Hypotheses	Substantiation	References
Buildings City centers Public infrastructure	+	Populated and/or frequently visited areas, high littering rates.	Ryan et al. (2018) Tasseron et al. (2020, 2023)
	-	High clean-up rates. Impervious surfaces facilitate transport of macrolitter outside of the considered area.	Mellink et al. (2022)
Recreational areas	+	Areas of high number of visitors, thus prone to high littering rates. Previous studies show that recreational areas and parks can be pollution sources.	Carpenter and Wolverton (2017)
	-	High clean-up rates due to the aesthetical value of some recreational areas.	
Vineyards Orchards	+	Leakage of items used in the agricultural sector, such as agricultural sheeting. Touristic visits in the wine sector, high littering rates.	Steinmetz et al. (2022)
	-	Low population densities, low littering rates.	
Forests Marshlands	+	Areas of touristic frequentation, can be prone to high littering rates. Dense tree and vegetation cover might induce low transport of items and high retention capacity, especially if in contact with rivers and lakes that might deposit items on the shores.	Pietz et al. (2021) Delorme et al. (2021) Mellink et al. (2022)
	-	Low population densities, low littering rates. High clean-up rates due to the aesthetical value of some forested areas.	
Other land	+	Areas where macrolitter could be discarded informally.	Sakti et al. (2023)
	-	Low frequentation and low littering rates.	
Roads	+	Proxy for densely populated areas and direct littering along roads. Accumulation observed at roadside ditches.	Matos et al. (2012) Pietz et al. (2021)
Rivers and canals	+	Pathways of macrolitter pollution, potential entry points into the environment. Accumulation and deposition along rivers.	van Emmerik et al. (2022)
	-	Rivers could mobilize items previously accumulated on riverbanks, thus acting as a removal factor of accumulated macrolitter.	van Emmerik et al. (2023)

3. Results and Discussion

A majority of consumables and industry/construction items

A total of 50,649 macrolitter items were sampled in Switzerland between 1 April 2020 and 31 May 2021 (48,239 on lake shores and 2,410 on riverbanks) were classified into 199 distinct categories, reflecting the diverse range of sources and types of macrolitter encountered. Among the lake survey locations, 34 categories were identified with a minimum count of 20 items observed during at least one survey. For the riverbank survey locations, the most abundantly encountered items were distributed across ten distinct categories. These top categories accounted for 82.9% of the total items found, 84.1% (n = 40,566) for lake shores, and 58.0% (n = 1,399) for riverbanks. The most abundant items were mainly identified as plastic material (89.9%) while other materials include glass (6.1%), metal (2.8%) and paper (1.1%). Among the most commonly found items, the top ten categories (Figure 2A) at lake locations consist of cigarette filters, fragmented plastics, expanded polystyrene, and food wrappers. The category of fragmented plastics includes various plastic types, such as foil, hard fragments, and foam. At riverbank locations (Figure 2B), top ten items include diapers and wipes, cigarette filters, glass bottles and pieces, and industrial sheeting. Among the ten most frequently found item categories at riverbank locations, seven of them also appear among the 34 most commonly found categories at lake shores. This indicates a good agreement among the most commonly found items between lake shore and riverbank locations. Tables A2 and A3 in Appendix B present a complete overview of top items abundance, their type and dominant material for both lake shore and riverbank locations.

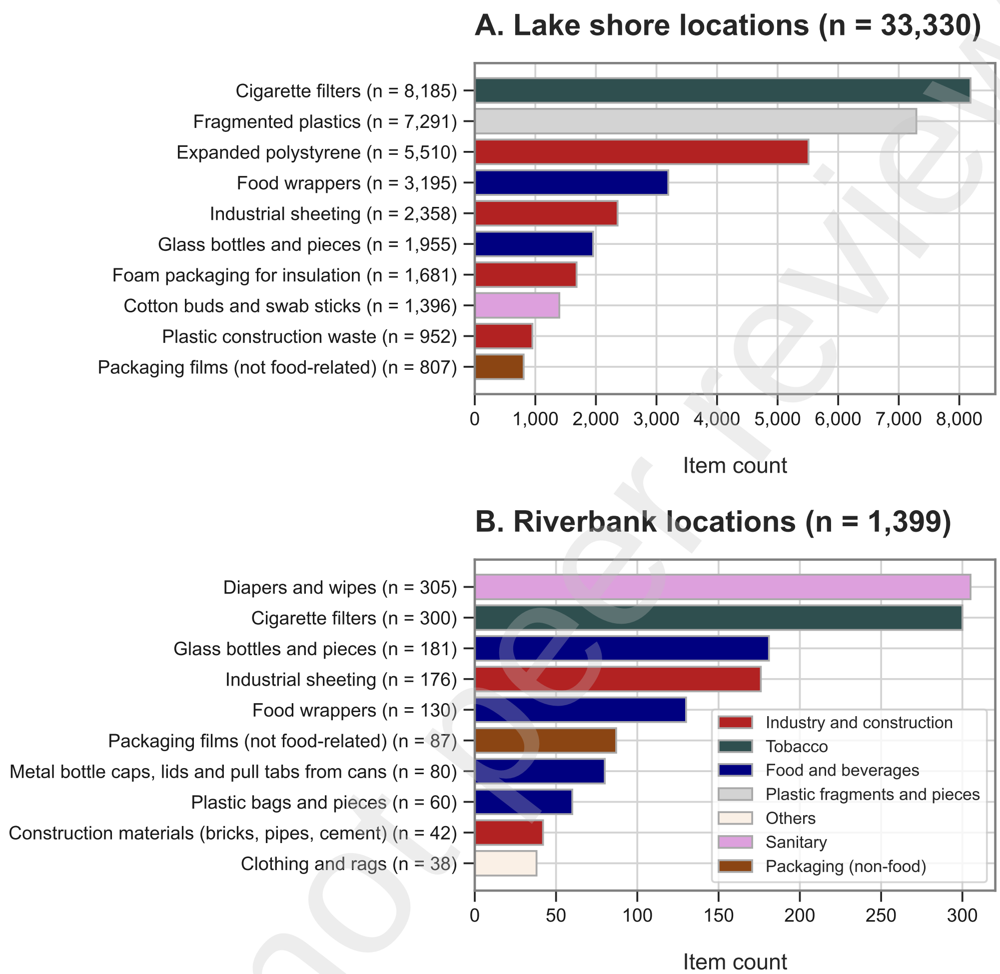

Figure 2: Top ten macrolitter items found in Switzerland (n = 34,729 - 68.6% of total items sampled) and their likely origin for both lake shore survey locations (A) and riverbank locations (B). These top ten items correspond to 69.1% (n = 33,330) and 58.0% (n = 1,399) of all sampled items at lake shore and riverbank locations, respectively.

A considerable amount of items (n = 10,924, 26.6% of total) can be attributed to the industrial and construction sectors (Table A4). Expanded polystyrene is often used as insulation material in the construction sector, and industrial sheeting is commonly used in the horticulture, industrial and construction sectors. These items are not associated with consumer littering behavior, suggesting that they may enter the environment unintentionally, either near their manufacturing sites, at construction sites where these materials are used, or during transportation. Items related to food and beverages (19.0%), as well as tobacco products (21.7%), contribute significantly to the top items. Together, these items make up for the highest share of items (*sim* 41%). The presence of consumable items can be attributed to direct littering by consumers, with food wrappings, packaging, cigarette filters, and glass bottles being commonly discarded on land by visitors (Kelley and Ambikapathi, 2016; Kolenda et al., 2021; Ballatore et al., 2022; Youngblood et al., 2022; Vanapalli et al., 2023). Additionally, plastic fragments and pieces also contribute significantly, accounting for 17.4% of the top items. Hypothesizing pathways for plastic fragments is more difficult, because of their reduced size, fragmented state, and omnipresence. Fragmentation and degradation could be the result of long residence times on both land and water. Further investigation into the transport pathways and sources of these fragmented items is required. The remaining types of plastic contribute to a lower proportion of the top items, each accounting for less than 10% (Table A4). Some sanitary products likely make their way into the environment at combined sewer overflows (CSOs) and stormwater outlets. Sanitary products were found in higher proportion at riverbank locations than at lake shore locations (21.8% and 5.2%, respectively).

Except from the higher share in items attributed to the industrial sector, the composition of the top macrolitter items found in Switzerland is similar to that found in other observational studies on macrolitter abundance across European waterways. Tramoy et al. (2019) found that plastic pellets, unidentified fragments and sticks (cotton buds and lollipop sticks) were the most abundant objects accumulated on the riverbanks of the Seine river, France. Other abundant items included expanded polystyrene, caps and industrial packaging films (Tramoy et al., 2019). Plastic fragments, food wrapping and packaging, caps and lids, cotton swabs and cigarette filters also feature among the top 20 items found on Dutch riverbanks (van Emmerik and Schwarz, 2020). These items were also among the top ten litter items collected on the riverbanks of the Adour river in France (Bruge et al., 2018). This consistency in macrolitter composition is likely the result of similar consumption patterns and waste management practices among European countries. Another explaining factor might be that transport and deposition affect specific litter items differently and that thus, the items commonly found on freshwater shores are those preferentially deposited, due to their characteristics and transport processes. Among the top macrolitter items found in the above-mentioned studies and in Switzerland, several categories indicates high amounts of caps and lids. In contrast, plastic bottles were rarely found. This could be due to the high recycling rate of plastic bottles and thus their removal from the environment. Another explanation could be that bottles in transport in the water would likely sinks into the lake or river, whereas the caps stay afloat and wash up on the shores due to the combined action of wind, current and discharge, as suggested by Bruge et al. (2018).

Roads and buildings are overall good predictors of macrolitter abundance

Among land-use features, roads and buildings resulted in the highest number of positive correlations (n = 18) with macrolitter items. Correlation coefficients varied significantly, ranging from 0.08 to 0.53. Out of these 18 correlations, 15 of them corresponded to both roads and buildings, indicating a strong relationship between these two factors. As much as 64.1% of top items were found positively correlated with roads, and 61.8% with buildings (Table A5). Among land-use features, roads and buildings resulted in the highest number of positive associations (n = 18) with macrolitter items. These results are consistent with previous observation-based studies that have identified roadsides and built-up areas are macrolitter accumulation zones (Matos et al., 2012; Tasseron et al., 2020; Pietz et al., 2021; Tasseron et al., 2023; Winston et al., 2023). Public infrastructure buildings displayed a positive correlation with 58.5% of top items (Table A5). Additionally, other land-use features related to urban coverage, such as city centers and recreational areas, also demonstrated significant and positive correlations with top macrolitter items, although to a lesser extent than buildings, roads and public infrastructure. One reason for this could be that city centers and recreational areas cover lower share of the total land-use area at survey locations (Table A1). Overall, land-use features related to urban coverage emerged as the most influential predictors of macrolitter abundance. This is particularly evident for items associated to direct consumption, such as tobacco, food and beverages and sanitary products. All tobacco-related items (cigarette filters and plastic packaging for tobacco) and plastic fragments and pieces exhibit significant correlations with multiple land-use features associated with urban coverage. Cigarette filters, the most prevalent item found throughout the study (n = 8,485), showed positive correlations with various land-use features related to urban coverage, supporting the hypothesis that these items tend to accumulate in areas where direct littering occurs (Vanapalli et al., 2023). Similarly, items linked to food and beverages often demonstrate frequent correlations with urban coverage features, including food wrappers, metal bottle caps, lids and pull tabs from cans, as well as lids and cap rings from plastic bottles and aluminum foil (specifically for lake shores). However, other food and beverages related items displayed limited associations with land-use features, resulting in 44.8% of food and beverages related items with less than three positive and significant associations with land-use features.

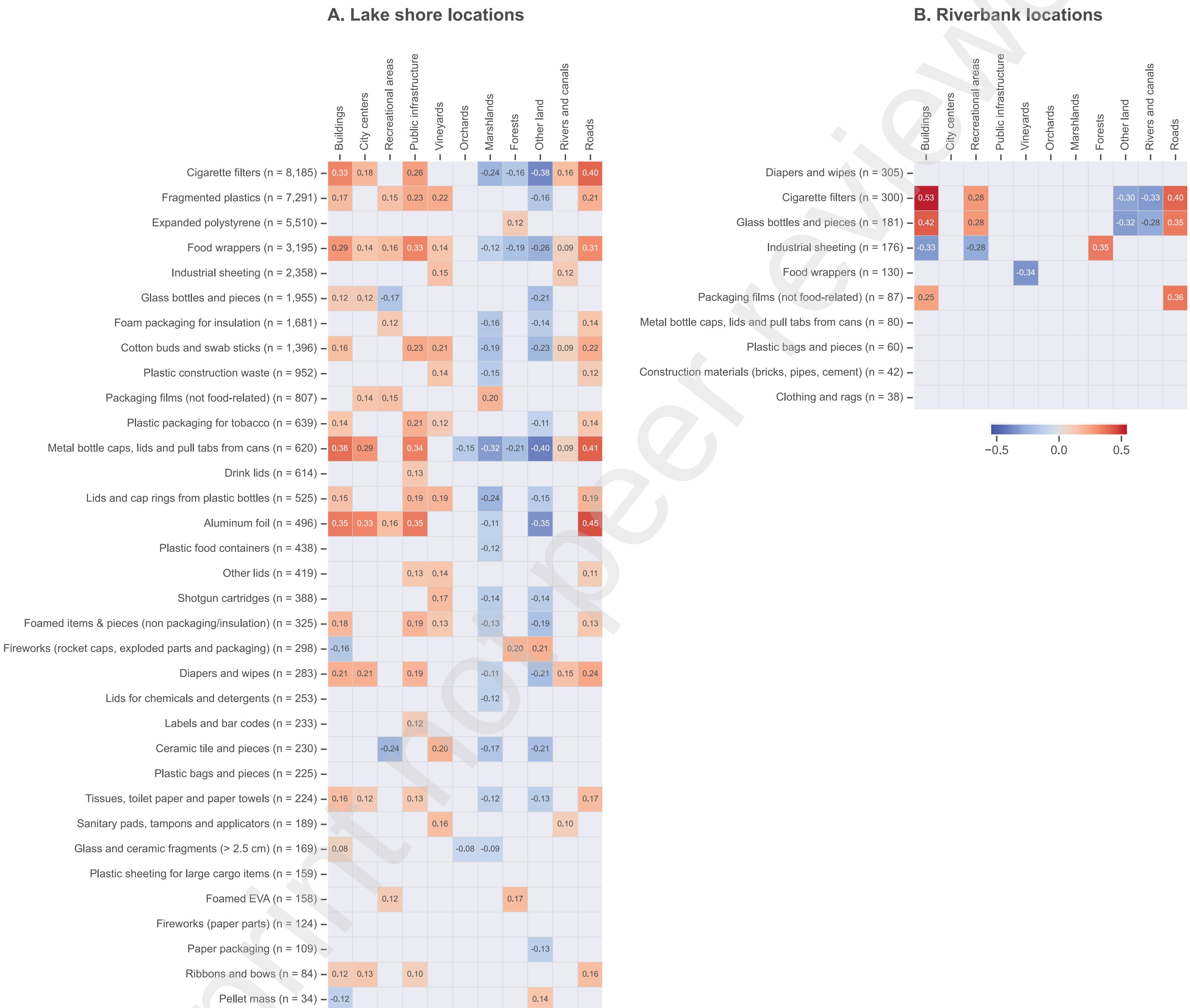

Figure 3: Correlation matrix for the most commonly found items on lake shores and riverbanks in Switzerland. Each square details the Spearman correlation coefficient (R) for p-values below 0.05 for each item category and land-use variable combination. For combinations where the p-value is below 0.05, no R value is indicated, as the relationship is considered non-significant.

Industry and construction related items show no positive correlations with land-use features (Table A6). Expanded polystyrene, industrial sheeting, foam packing for insulation, plastic construction waste, plastic sheeting, foamed EVA and other construction materials have no or very few (less than three) positive significant correlations with land-use variables (Figure 3). Three factors may explain the absence of positive associations between items related to the industrial and construction sector and land-use features. First, the spatial distribution of these items along riverbanks and lake shores may be diffuse and thus independent of land characteristics. Previous research found that expanded polystyrene items are likely to be transported over longer distances in rivers than other items (Ryan, 2021). Because of their low densities and thus high buoyancy, these items are more likely to be mobile in the environment, notably through wind action. Thus, changes in land-use features may not significantly impact the accumulation of these items in the environment. Second, the leakage and supply of industrial and construction-related items into the environment could also be spatially diffuse, resulting in limited or no discernible relationship with land-use features. Finally, it is worth noting that the available land-use dataset does not differentiate buildings and facilities specifically associated with the production and use of industry related items. Buildings related to the industrial and construction sector are not distinguished from other types of buildings. As a result, establishing correlations between potential production and use areas, and areas of accumulation, becomes difficult.

Our research supports our initial hypothesis concerning forests, marshlands, and other land, indicating that areas with lower population densities and minimal human activity exhibit reduced littering rates and consequent accumulation. In the case of these land-use features, a predominant proportion of significant negative correlations were observed, accounting for 28.3%, 46.1% and 65.6% of the top items for forests, marshlands and other land, respectively (Table A5). This pattern indicates a reduced occurrence of macrolitter items in these environments. This was particularly the case for consumable items, such as cigarette filters, food wrappers, cotton buds and swab sticks and metal bottle caps, lids and pull tabs from cans (Figure 3), all of which exhibited statistically significant negative correlations with forests, marshlands, and other land. It is important to note that 'Other land' primarily encompasses agricultural and unproductive land, where minimal direct littering of consumable items can be expected. Additionally, agricultural land could involve plastic film and sheet use and leakage, as documented by

MacLeod et al. (2021). Our results also show notable positive links between expanded polystyrene (EPS) and foamed ethylene-vinyl acetate (EVA) with forests and other land. Interestingly, plastic bags and plastic pieces also exhibited a positive correlation with forested areas. However, the exact reasons behind this correlation remain unclear, and further investigation is needed to understand why such a relationship exists. Furthermore, the positive correlations observed for EPS, foamed EVA, and industrial sheeting (in river locations) may be attributed to their sources being primarily located outside of urban areas or their potential for longer-distance transport.

Among the land-use features related to agricultural use, only vineyards showed positive correlations with a significant portion of the top items, accounting for 42.3% of them (Table A5). Among the items displaying a positive association with vineyards, some can be directly linked to their utilization in this agricultural sector, such as industrial sheeting, foamed items, and non-packaging/insulation pieces. Additionally, the presence of other items positively correlated with vineyards suggests that these areas are frequently frequented, resulting in observable littering of consumable items. This is evident in items such as plastic fragments, food wrappers, plastic packaging for tobacco, as well as lids and cap rings from plastic bottles (Figure 3). Orchards displayed minimal significant correlations with the top macrolitter items, indicating that they are not a reliable indicator of macrolitter accumulation.

4. Synthesis and outlook

The results of this study have several implications, particularly regarding the design of clean-up and reduction strategies. We found that land-use features, in particular those related to urban coverage such as roads and buildings, are robust indicators for the abundance of the majority of macrolitter items on riverbanks and lake shores. Close to two-thirds of the top items found on lake shores and riverbanks were positively and significantly correlated with roads and buildings (64.1% and 61.8%, respectively). For items strongly correlated with land-use features, such as tobacco-related products and items from take-out consumption, localized mitigation projects are likely to yield significant reductions in their abundance. These efforts can focus on targeted interventions at local (municipal) geographic scales to address littering hotspots effectively (Doolin and Zhang, 2015; Kelley and Ambikapathi, 2016). Such approaches acknowledge the need for behavioral changes and community engagement to effectively reduce macrolitter abundance and minimize its environmental impact. Therefore, it is crucial to address the local inputs and human component inherent in macrolitter pollution for the development of comprehensive and sustainable litter management strategies. Certain macrolitter items, particularly those associated with the industrial and construction sector, showed limited or no associations with land-use features. However, it is important to note that our study did not have data available to directly test the relationship between macrolitter abundance and both manufacturing and construction sites. Therefore, it is possible that such an association exists, but we were unable to capture it with the current data. Assuming no relationship between industry-related items and land-use features, it would be advisable to implement strategies targeting these items at a regional scale, as they appear to be less influenced by specific land-use characteristics. By addressing the specific sources and practices within this sector, clean-up efforts can effectively minimize the occurrence of such items. Overall, both regional and local mitigation strategies are necessary for achieving substantial litter reduction, as our study identified a considerable proportion of macrolitter items associated with land-use features, as well as items that exhibited no such associations. By combining efforts at different geographic scales, stakeholders can create comprehensive reduction and clean-up strategies to tackle macrolitter pollution.

Furthermore, our study provides insights into the transport behavior of macrolitter. We highlight the spatial proximity of items to their potential leakage sources, as evidenced by the numerous significant correlations found between tobacco, food, and drink-related items and land-use features associated with urban coverage. This supports the findings of previous studies, highlighting that macrolitter items are not transported over long distances in rivers (Tramoy et al., 2020; van Emmerik et al., 2022; Lotcheris et al., submitted) and over land (Kelley and Ambikapathi, 2016; Ballatore et al., 2022; Cowger et al., 2022). Macrolitter items tend to be found in the vicinity of their pollution sources (Kelley and Ambikapathi, 2016; Ballatore et al., 2022; Cowger et al., 2022; Schuyler et al., 2022). However, no studies quantified the transport distances of macrolitter in lakes. The high proportion (18%) of fragmented plastics found at lake shore locations may suggest that fragmentation and degradation of entire items occurred during transport in lakes. However, fragmentation processes could also take place through over land transport or when accumulated at lake shores. In addition, our results emphasize the stochastic nature of macrolitter pollution, with local factors and human behaviors contributing to the observed variability in spatial distribution (Cowger et al., 2022). In their investigation of macrolitter transport mechanisms at roadsides, Cowger et al. (2022) considered factors such as runoff, wind direction, and human travel. They found that human travel played a predominant role in macrolitter accumulation along roadsides. Understanding this stochastic component raises important considerations for incorporating it into predictive models. Most studies on macrolitter abundance have so far primarily investigated the role of environmental factors such as runoff, wind, river discharge, water levels, flood occurrence and magnitude (Mellink et al., 2022; Roebroek et al., 2021b,a; van Emmerik et al., 2023). Our findings highlight the need to shift towards including urban coverage and human littering as key factors in predictive models (Tasseron et al., 2023). By integrating the stochastic element and the influence of human activities, we can improve the accuracy and effectiveness of predictive models for macrolitter abundance and develop more targeted strategies for its prevention and management. These efforts could include a greater focus on identifying source locations of macrolitter, such as restaurants, convenience stores, and supermarkets, as highlighted by Kelley and Ambikapathi (2016) and Ballatore et al. (2022).

5. Conclusions

We investigated macrolitter composition at lake shores and riverbanks in Switzerland. Items that can be related to consumable products, such as tobacco and food and beverages products make up for the highest share of items (41%). Industry and construction related items also constitute a significant proportion of macrolitter items, accounting for nearly 27% of the top items found on lake shores and riverbanks in Switzerland.

We found that urban coverage features, particularly roads and buildings, are robust indicators for the abundance of the majority of macrolitter items on riverbanks and lake shores ($\sim$ 60% of top items), notably items related to consumption. However, items related to the industrial and construction sector show limited or no correlations with land-use features at the survey locations. Overall, urban land-use features are good predictors for the most commonly found macrolitter items, with the notable exception of industry related items.

Our results show the need for targeted approaches in litter reduction strategies at different geographical scales to achieve effective impact. Local-scale efforts are likely to yield significant results for consumable products, while regional targeted strategies and actions may be more appropriate for other types of items, including those related to the industry. Furthermore, we emphasize the importance of further research to comprehend the dynamics of litter transport over land and within freshwater systems. Such knowledge is crucial for establishing more comprehensive and effective strategies to mitigate macrolitter pollution and safeguard our aquatic environments.